AC 2011-2171: ENGINEERING WITH ELECTRICITY AND MAGNETISM: A GUIDED-INQUIRY EXERCISE FOR HIGH-SCHOOL STUDENTS TO ENHANCE UNDERSTANDING OF FARADAY'S AND LENZ'S LAWS

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Engineering with Electricity and Magnetism: A Guided-Inquiry Exercise for High-School Students to Enhance Understanding of Faraday's and Lenz's Laws

Introduction

Many high-school students and teachers find the concepts of Faraday's and Lenz's laws to be difficult to comprehend and often cannot see their relevance to our everyday lives. In many cases, these topics are omitted from the high-school curriculum or given a cursory coverage due to the teachers' lack of comfort with this material. However, these two laws are a critical foundation for many of the key technological innovations which have taken place over the past 100 years, particularly in the area of electricity generation. As such, it is important that all high-school students develop a basic comprehension of these laws and how they can be used in an engineering context.

As part of the high-school outreach effort within our Electrical and Computer Engineering department, we have developed a guided-inquiry exercise which is designed to enhance the understanding of these two fundamental laws. This hands-on exercise enables high-school students to discover through their own efforts the essential ideas behind these laws. At the same time, the students gain a greater appreciation for the role of engineers in society by working through the steps to solve a simple design problem.

In order to share this exercise with as many students and teachers as possible we have begun to present this as a workshop to high-school teachers at regional conferences of science teachers. The primary purpose of this paper is to fully describe this hands-on exercise and how the guided-inquiry method was implemented to highlight the most important concepts behind Faraday's and Lenz's laws. We will also discuss the supplementary material that was prepared for the teachers, so that they would have the tools to highlight the engineering developments which have resulted from these laws. In addition, we will present some preliminary survey data that we have gathered from these conferences.

Description of the Exercise on Faraday's and Lenz's Laws

The primary purpose of this exercise was to enable high-school physics students to "discover" through direct experimentation what these laws actually mean and how they can impact society. No prior understanding or knowledge of these two abstract laws is assumed. The hope is that by working through this exercise before seeing the theoretical and mathematical details of these laws in class, the students will gain a greater appreciation for the practical aspect of these laws.

Experimental Kit

This learning experience is based around a kit which consists of a modified off-the-shelf "electromagnetic flashlight"¹, a custom-made circuit board, and a pair of connecting wires. The components of this kit are shown in Figure 1. The flashlight was modified slightly by adding a connector to the side of the flashlight, which enabled a direct connection to one of the coils inside the body of the flashlight. The normal operation of the flashlight was not interfered with.

The flashlight serves two main purposes within the exercise. First, it provides a simple implementation of a coil/magnet assembly for a relatively low cost (~\$20), and in a package in which the movement of the magnet relative to the coil can be easily observed. Second, the flashlight illustrates how Faraday's law can be used to solve a very practical problem, i.e., the generation of light. Since the electromagnetic flashlight is one which has no replaceable batteries in it the light created comes directly from energy generated through the shaking of the flashlight. The students can see this by using the flashlight in its normal operation.

Figure 1. Components of the Experimental Kit

The second main component of this kit is the custom-made circuit board. This board consists of two separate parts, each of which is a very simple circuit. The first circuit has a connector attached to a green light-emitting diode (LED). Thus, by using the connecting wire these students can directly connect the coil in the flashlight to this green LED. The second circuit also consists of a connector and an LED (red in this case), but it also includes a few other components (a capacitor and a diode/resistor combination which acts as a rectifying circuit). Anyone interested in the parts list and schematic of these circuits can contact the authors for this information.

Guide-Inquiry Experiments

With the kit as the foundation, the exercise makes use of the discovery method as a teaching tool which allows the students to develop their own descriptions of these two fundamental laws. The plan is that each group of students is provided with a guided-inquiry framework through a set of three experiments. These experiments are described in Table 1, and the worksheets along with the answer key are presented in Appendix A. Anyone interested in using these exercises in class can contact the authors to receive a softcopy of the blank worksheets.

By working through each of these experiments, students are encouraged to put their own words to their observations and thus develop statements of Faraday's and Lenz's laws through their own efforts. This is a proven technique for improving their understanding and retention of the core concepts, and their motivation to learn more^{2,3}.

Table 1. The Three Guided-Inquiry Experiments to Discover Faraday's and Lenz's Laws

Experiment	Basic Steps	Main Conclusions
<u>Experiment #1</u> <i>The Great Energy Converter</i> (Discover the basics ideas behind Faraday's law)	<ul style="list-style-type: none"> • Connect the coil of the flashlight to the green LED on the circuit board. • Shake the flashlight and observe what happens with the green LED. • Consider what is required for the LED to light up. • Come up with a statement concluding your observations. 	<ul style="list-style-type: none"> • The rate at which the LED turns on relates to how quickly the flashlight is shaken. • This means that kinetic energy is converted to "light" energy. • Since an LED requires a flow of electrical charges to produce a light, one can conclude that the movement of the magnet through a coil creates a flow of electrical charges through the LED (simple statement of Faraday's law).
<u>Experiment #2</u> <i>Let's Do Some Engineering</i> (Make use of Faraday's law to solve an engineering design problem based around the generation of "light" energy)	<ul style="list-style-type: none"> • Discuss why the situation of Experiment #1 would not lead to a very practical "flashlight". • Come up with a plan of how to improve the "usability" of this "flashlight" design. • Connect the coil of the flashlight to the second circuit on the circuit board (the one with the red LED), and shake the flashlight again. • Determine the main purpose for this second circuit, and how does this relate to the plan that you came up with to improve the "flashlight's" usability. 	<ul style="list-style-type: none"> • Since the LED lights only with the magnet moves through the coil, constant motion is required for a continuous light source. This makes it impossible to direct the light to a specific area. • To improve this design, one needs to store the energy generated by the magnet moving through the coil. • The purpose of the second circuit is to store this electrical energy generated through the movement of the magnet through the coil
<u>Experiment #3</u> <i>No Free Energy Here</i> (Discover the basic ideas behind Lenz's law)	<ul style="list-style-type: none"> • Disconnect the coil from the circuit board. • Shake the flashlight for two cases (a) connect the two wires of the coil together, and (b) disconnect the two wires of the coil from each other. • Observe the classroom demonstration involving an oscillating magnet⁴. • Relate these observations to the description of Faraday's law that you developed in Experiment #1. • Consider how this relates to the conservation of energy. 	<ul style="list-style-type: none"> • When the coil wires are connected together the overall displacement of the magnet within the coil is less than when the coil wires are disconnected • This lack of displacement when the coil wires are connected together indicate that the electrical current generated by the moving magnet through the coil creates its own magnet field that opposes the movement of the magnet (simple statement of Lenz's law). • Lenz's law is simply a restatement of the law of conservation of energy.

Science Teacher's Workshop Presentation

This guided-inquiry exercise was first developed as an aid for high-school physics teachers in teaching these abstract concepts as part of their Grade 11 Physics curriculum. To disseminate this learning exercise to as many students as possible it has been presented as a workshop at two regional conferences for high-school science teachers. Every workshop attendee was given a kit which they could take back to their class to use as a demonstration model. This model could be quite easily replicated for larger classes, or could be shared amongst a number of groups of students as they work through the experiments.

The workshop was run in a similar manner to how the actual exercise would be used in class, so that the teachers had an idea of what their students would be experiencing. In addition, some of the finer details were also discussed. This included: (a) how these observations and conclusions related to the mathematical representations of these laws (something which was not expected from the students), (b) the part list and theory behind the second energy-storage circuit on the circuit board, and (c) the actual operation of the LED.

Since one of the purposes for this exercise was to give the students a greater sense of what electrical engineering is about, there was also some discussion in the workshop on related applications of Faraday's and Lenz's laws within society. As well, a brief discussion of electrical energy storage was presented since this was the main tool used to solve the engineering design problem within this exercise. A set of additional notes that included more details about these applications and other suggested classroom demonstrations for each topic was also given to the high-school teachers. These notes are presented in Appendix B.

Workshop Participant Survey Results

At the end of the most recent workshop, presented in the fall of 2010, a survey was administered. Twenty-two of the 30 participants completed the survey and the results are summarized in Table 2. Overall, the workshop attendees were quite positive about their workshop experience, with all of them agreeing that the workshop was an enjoyable experience. The teachers seemed to be quite enthusiastic about incorporating real-life applications of Faraday's and Lenz's laws into their classroom (77% strongly agreeing with this statement), and many of them (68%) indicated that they plan to provide their students with an experience of how these laws can be used to solve an engineering design problem. As well, 77% stated that they strongly agreed with the notion of helping their students to better understand the role of the electrical engineer within society. Also, from these results it seems that for about half of the attendees, the workshop helped to increase their understanding of these two laws. This may be partly because many of them already came into the workshop quite comfortable with these concepts. Indeed the workshop seemed to attract a rather wide range of teachers, some that had taught physics for many years and some that were fairly new to teaching this subject.

Table 2. Workshop Attendee Survey Results (22 respondents)

Question	Attendee Response (5 – Strongly Agree, 4 – Somewhat Agree, 3 – Neutral, 2 – Somewhat Disagree, 1 – Strongly Disagree)	Question Average
Overall, I found this workshop to be quite enjoyable.	Strongly Agree 91% Somewhat Agree 9% Neutral 0% Somewhat Disagree 0% Strongly Disagree 0%	4.91
This workshop has increased my understanding of Faraday’s law and Lenz’s law.	Strongly Agree 50% Somewhat Agree 41% Neutral 9% Somewhat Disagree 0% Strongly Disagree 0%	4.41
This workshop has enhanced my appreciation for how a capacitor can be used as an electrical energy storage device.	Strongly Agree 41% Somewhat Agree 50% Neutral 9% Somewhat Disagree 0% Strongly Disagree 0%	4.32
This workshop has enhanced my appreciation for how basic engineering principles can be applied to solve a societal problem using Faraday’s law.	Strongly Agree 64% Somewhat Agree 32% Neutral 4% Somewhat Disagree 0% Strongly Disagree 0%	4.59
Based on this workshop, I plan to incorporate more real-life applications into my classes on Faraday’s law and Lenz’s law.	Strongly Agree 77% Somewhat Agree 18% Neutral 5% Somewhat Disagree 0% Strongly Disagree 0%	4.73
Based on this workshop, I plan to provide my students with an experience in which they can use Faraday’s law and Lenz’s law to “engineer” a solution to a problem.	Strongly Agree 68% Somewhat Agree 27% Neutral 5% Somewhat Disagree 0% Strongly Disagree 0%	4.64
Based on this workshop, I plan to help my students better understand the role of the electrical engineer in society.	Strongly Agree 77% Somewhat Agree 9% Neutral 14% Somewhat Disagree 0% Strongly Disagree 0%	4.64

In order to assess if these teachers have actually incorporated this engineering exercise into their classroom and if it was a successful experience, a follow-up survey will be administered later this year. To assess the ultimate goals of the exercise will require direct interaction with the high-school students who work through this exercise. This interaction could be a combination of student surveys, observations of the students working through the exercise, and interviews with the students. The outstanding research questions associated with this project are:

- (a) Do high-school students develop a greater understanding of Faraday's and Lenz's laws through the completion of this exercise?
- (b) Is their understanding of these laws impacted by the timing of this exercise? Meaning does it matter if it is done prior to or after a theoretical presentation of the material?
- (c) Do high-school students develop a greater understanding of how Faraday's and Lenz's laws can be used to solve engineering problems?
- (d) Do high-school teachers find that the workshop and supplemental materials provide them with enough support to implement this exercise into their classroom?
- (e) Do high-school teachers find that incorporating this exercise into their classroom enables them to provide the students with a greater understanding of the role of electrical engineers within society?

Conclusions

A new guided-inquiry exercise has been developed to enable the better understanding of Faraday's and Lenz's laws at the high school level. The exercise allows the students to come up with their own statements of these fundamental laws through their observations from a set of three experiments. Through the use of the discovery method, it is hoped that this exercise gives the students a more substantial learning experience than they would have had with traditional classroom teaching.

The exercise is based upon experiments using a custom developed kit with the main component being an electromagnetic flashlight. The set of experiments are designed so that the students can discover these laws as well as solve an engineering design problem in the process. This design experience provides the students and the teacher with the opportunity to discuss in greater detail the role of the electrical engineer within society.

In an effort to disseminate this exercise to as many high-school students as possible, this exercise has been presented at two regional conferences for high-school science teachers. Survey results from 22 attendees at the most recent of these conferences indicate that the teachers found the workshop and the exercise to be quite beneficial in developing their understanding of these laws and in highlighting how Faraday's law can be used to solve practical problems within society. Indeed, 91% of the respondents agreed that the workshop helped to increase their understanding of these laws, and 96% agreed that the workshop enhanced their appreciation for how basic engineering principles can be applied to solve a societal problem using Faraday's law. These are good signs that this workshop has made a positive impact with the attendees and that this exercise has the potential to translate into successful learning experiences for their students.

Bibliography

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Appendix A: Guided-Inquiry Experiments on Faraday's and Lenz's Law with Answer Key

Experiment #1 – The Great Energy Converter

In this experiment, you will discover the law of physics which is responsible for nearly all of the electricity generation within our society. If it had not been for the great electrical engineers that first applied this law our world would be unrecognizable.

Exercise 1.1

- 1) Using the pair of wires, connect the flashlight to the green light emitting diode (LED) on the electronics board (Circuit #1).
- 2) Complete the following tasks and record your observations in the table below. Compare your results with those of the person to your left.

Task	Observations
Shake the flashlight <i>slowly</i>	<ul style="list-style-type: none">○ <i>As the flashlight is shaken the green LED lights up.</i>○ <i>In other words, the LED lights up as the magnet moves through the coil.</i>
Shake the flashlight <i>quickly</i>	<ul style="list-style-type: none">○ <i>As the flashlight is shaken faster the LED flashes quicker.</i>○ <i>Each time the magnet passes through the coil the LED flashes once.</i>

Question 1.1:

Clearly there must be energy coming from somewhere since the LED lights up. With your partner, pair up with the two people to your left. As a group, determine what is the source of this energy?

- *It has been observed that the movement of the magnet through the coil causes the LED to light. Therefore, it can be concluded that it is the mechanical motion of shaking the flashlight that is the source of the energy. This kinetic energy is converted into light energy. This kinetic energy comes from the contraction of the muscles which are powered by the food that has been eaten. Ultimately, this energy has its source in the sun.*

Experiment #1 – *The Great Energy Converter (continued)*

Question 1.2:

The fundamental requirement for an LED to light up is the same as that for a regular lightbulb. Given this, work with your partner to determine what is this fundamental requirement?

- *In order to light up an LED or a lightbulb an electrical current is required to flow through them. This means that electrons must be “pushed” through the LED or lightbulb by some source of electricity. For example, this source could be a battery.*

Question 1.3:

If we told you that the observations from this exercise are due to something that we call “Faraday’s Law”, how would you describe this “law”? Come up with your own description and then discuss this with your partner.

- *The main observation was:*
Each time the magnet moves through the coil the LED lights up.
- *Since the LED requires electrical current to flow through it to light up, we can say that “Faraday’s Law” could be:*
“When a magnet moves through a closed coil, an electric current is created. This is called an induced current”

Experiment #2 – *Let’s Do Some Engineering*

In this experiment you will have some experience in what an electrical engineer does. First, you must identify the problem to be solved. Second, you must figure out a solution which both solves the problem and is realistic, meaning that it can be built.

Question 2.1:

Let us consider the main observation of Experiment #1 in greater detail. For the situation of Experiment #1, in which the coil was directly connected to the LED, explain why this type of “flashlight” would be of no practical use.

- *Since the LED flashes only when the magnet **moves** through the coil, the flashlight would have to be continually shaken to produce a steady beam of light.*
- *This means that we would have very little control over where the beam of light was directed, which would make this “flashlight” of little practical use.*

Experiment #2 – Let’s Do Some Engineering (continued)

Question 2.2:

Now put on your electrical engineering hats. As a group of four, come up with a plan to improve the “usability” of this “flashlight”?

- *The main goal would be to create a flashlight that provides a steady beam of light for as long as possible. This would be our design specification.*
- *To meet this specification, we need a way to **store** the electrical energy generated by the movement of the magnet through the coil.*
- *This means that we need to add to our flashlight an electrical energy storage device.*

Exercise 2.1:

Prior to this workshop, we have done a little electrical engineering ourselves and came up with our own plan, or design, to make this “flashlight” usable. Test out our design by:

- 1) Disconnecting the flashlight from Circuit #1 and connecting it to Circuit #2 (the blue connector on the electronic circuit board). Recall, that the red LED is identical to the green LED in Circuit #1, it just has a different colour.
- 2) Slowly shake the flashlight. How does the performance of this flashlight design compare with the “flashlight” design of Experiment #1? Record your observations in the table below, and compare these with your partner.

Observations
○ <i>For this design, the red LED does not flash, but stays lit for a much longer period of time (approximately 15 seconds).</i>

Question 2.3:

With your partner, determine the fundamental purpose of Circuit #2, and discuss any other options for storing the electrical energy that is generated as the magnet moves through the coil?

- *The purpose is to act as an electrical energy storage device*
- *The largest piece in this circuit is a 1000 μF capacitor which stores the electrical energy*
- *The other three pieces of the circuit (not including the LED) are there to ensure that the capacitor properly stores and then releases its energy.*
- *One other option for storing electrical energy would be to use a rechargeable battery. In fact, this is the technique that is used in the flashlight that you have been given.*

Experiment #3 – No Free Energy Here

This experiment is focused on Lenz's law, which is closely related to Faraday's law. You will see that if this law did not exist, the world would behave in a very strange way.

Exercise 3.1:

- 1) Disconnect the wires from the electronics board.
- 2) Complete the following tasks and record your observations in the table below. Compare your results with those of your partner.

Task	Observations
Hold the flashlight horizontally and slowly shake it back and forth. Make sure that the two bare ends of the wires are not touching each other. How far does the magnet move?	<u>Experiment Case #1</u> : Wires not connected together (coil open) <ul style="list-style-type: none"> ○ <i>About one-half of the magnet exits the coils both at the top and the bottom as the magnet is shaken.</i>
Hold the two bare ends of the wires together such that they are well connected to each other. Again, slowly shake the flashlight horizontally and observe the movement of the magnet. Try to replicate the same strength of shaking as you did for the first task in this exercise. How far does the magnet move for this case?	<u>Experiment Case #2</u> : Wires connected together (coil closed) <ul style="list-style-type: none"> ○ <i>The magnet is now not visible at all as it moves. None of it exits the coil either at the top or at the bottom.</i>
Consider the demonstration that was shown. What are your main observations for the cases in which the coil is not connected to itself, and when it is connected to itself ("shorted out")?	<u>Demonstration Case #1</u> : Coil not connected to itself <ul style="list-style-type: none"> ○ <i>The magnet on the spring moves up and down freely within the coil.</i> ○ <i>It moves up and down approximately 20 times before it stops moving.</i>
	<u>Demonstration Case #2</u> : Coil connected to itself ("shorted out") <ul style="list-style-type: none"> ○ <i>The magnet on the spring moves up and down only a few times before it stops moving.</i>

Experiment #3 – No Free Energy Here (continued)

Question 3.1:

With your partner, determine how this relates to Faraday's law. In particular, use Faraday's law to explain the difference in your observations for the two cases. Recall, that Faraday's law as we have discovered it can be stated as:

"When a magnet moves through a closed coil, an electric current is created. This is called an induced current"

- *Since there is a magnet moving in a coil, an electric current can flow. However, for an electric current to flow there must be a closed conducting path.*
- *This means that for the case where the coil is not connected to itself there is no induced current that flows (the coil is open).*
- *For the case where the coil is shorted out, there is an induced current that flows. Recall, that every current has a magnetic field, so this induced current has its own "induced magnetic field".*
- *Since the magnet slows down when the coil is shorted, this shows that the induced magnetic field **opposes** the magnetic field of the moving magnet.*
- *In effect, when the coil is shorted out there is a "braking effect" on the magnet.*
- *This is the essence of **Lenz's law**. It can be stated as:*

"The magnetic field that is induced, or created, by a magnet moving through a closed coil will always act in opposition to the original magnetic field of the magnet"

Question 3.3:

Suppose that we lived in an alternate universe in which we repeated this same demonstration. In this alternate universe the observations for this same demonstration were:

- (a) For the case of where the coil was not connected to itself, the magnet moved freely and moved up and down about 20 times before coming to a stop.
- (b) For the case of where coil was shorted out, the magnet moved up and down with increasing speed and never came to a stop.

As a group of four, discuss which fundamental law of physics these observations (and thus this alternate universe) violate?

- *Given these observations there is no longer a braking effect on the magnet by the induced magnetic field, but instead the movement of the magnet is increased by the induced magnetic field.*
- *Considering the energy in the system, there is a small amount of potential energy at the start when the spring is stretched. As the magnet moves, there appears to be a limitless supply of kinetic energy since the magnet never stops. This violates the conservation of energy since there turns out to be more kinetic energy than there was potential energy.*
- *This shows us that Lenz's law is essentially just a **restatement of the law of conservation of energy**.*

Appendix B: Additional Material Given to Workshop Participants

Additional Material

Electrical and computer engineering (ECE) is a very exciting branch of applied science and engineering as it covers a wide range of applications. The heart of ECE is focused around the harnessing of electricity to solve society's problems and improve the world we live in. This could involve the development of highly efficient solar energy collectors, the design of complex software systems which can improve the functionality of wireless communications, or the control of unmanned vehicles such as airplanes or cars. Each area in which electrical and computer engineers work requires a strong understanding of the fundamental mathematics and sciences, such as electricity and magnetism.

We hope that this additional material will add to the different aspects of electrical and computer engineering that you bring into your classroom. We have tried to highlight some of the most interesting and relevant engineering applications of the main topics of this workshop, namely Faraday's law, Lenz's law, and Electrical Energy Storage (Capacitors).

Faraday's Law

Summary

During the workshop we have determined that Faraday's law can be stated as:

"When a magnet moves through a closed coil, an electric current is created. This is called an induced current"

In more general terms we can state Faraday's law as:

"When a magnetic field changes in the presence of a conducting material, an electric current is induced in the conducting material."

This means there are two main components to Faraday's law:

- 1) *A changing magnetic field.* The change can be caused by:
 - a. The relative movement between a permanent magnet and the conducting material, and/or,
 - b. The time variation of a source current, i.e., an AC current, which has its own time-varying magnetic field.
- 2) *A conducting material.*
 - a. If the conducting material forms a closed path, then an induced current can flow in the material which results in an opposing induced magnetic field.
 - b. If the conducting material does not form a close path (e.g., a ring with a slit cut into it) then an induced current cannot flow and there is no opposing induced magnetic field.

Faraday's Law (continued)

Engineering Applications

There are now innumerable ways in which engineers have applied Faraday's law to solve major engineering problems over the last century. Many examples can be found at the Wikipedia page on Electromagnetic Induction, http://en.wikipedia.org/wiki/Electromagnetic_induction

Some of the most important and current applications are:

1) *Electricity Generation*

The vast majority of our electricity generation comes through the conversion mechanical energy to electrical energy. The mechanical energy is a result of the turning of large turbines through:

- a) The flow of water (hydroelectric dams or tidal power)
- b) The steam created through nuclear fission or the burning of fossil fuels (nuclear and coal-fired power plants)
- c) The flow of air (wind turbines)

The part of these turbines consist of a magnetic field, that changes through the mechanical rotation, and a set of conducting coils in which the induced current exists.

2) *Credit and Debit Card Readers and Computer Hard Drives*

- Most credit and debit cards have the user's information "written" into the magnetic stripe on the back of the card.
- This stripe acts as a set of small "permanent magnets".
- As the card is swiped through a reader, there is a changing magnetic field in the presence of a conducting material, since these small "permanent magnets" are being moved past a conducting loop in the reader.
- The induced current in the conducting loop can be "interpreted", which results in the card's information being "read".
- A very similar process is at the heart of how data is stored in computer hard drives.

Faraday's Law (continued)

3) *Electrical Transformers*

- These devices consist of:
 - a) One coil (the primary) that carries an AC current, which creates a changing magnetic field.
 - b) This changing magnetic field interacts with the second coil (the secondary), which will have an induced current flowing through it as a result of Faraday's law.
 - c) By adjusting the number of turns in the two coils you can create either step-up (voltage across the second coil is larger than the voltage across the first coil) or step-down (voltage across the second coil is smaller than the voltage across the first coil) transformers.
- These devices are extremely useful in a wide variety of applications, such as stepping down the high voltages that are distributed by the power companies before the electricity enters residential units.

Possible Classroom Demonstration

Oscillating Magnets

Source: U.C. Berkeley Physics Lecture Demonstrations, available at <http://www.mip.berkeley.edu/physics/physics.html>

Faraday's Law (continued)

This is a great demonstration which is relatively simple to put together. The magnets can be easily connected to the springs by using small metal nuts (from extra bolts lying around). Even moderately strong magnets (e.g., alnico bar magnets) with coils, or solenoids, that have a reasonable number of turns (>400 turns) can demonstrate the main effect.

The reason why this is such a useful demonstration is that it illustrates the two most powerful applications of Faraday's law in today's society: *electricity generation* and the *motor principle*. As the first magnet is moved in Coil A, the mechanical energy is converted into electrical energy through the power of electromagnetic induction. As this electrical energy is transferred to Coil B, this is converted back into mechanical energy which causes the second magnetic to move up and down. All this is done through the "invisible" and "mysterious" nature of the magnetic fields.

Lenz's law can also be qualitatively demonstrated by reversing the orientation of one of the magnets, meaning that you connect the other end of one of the magnets to the spring. For one orientation, the magnets will oscillate together. For the other orientation the magnets will oscillate opposite to each other. This demonstrates that the "type", or orientation of magnetic field that is induced depends on the orientation of the original magnetic field.

Lenz's Law

Summary

There is a peculiar nature about the qualitative form of Faraday's law, which is the one that we have developed in this workshop. It tells us that a magnetic field will be induced in a conducting material if a changing magnetic field is present, but it does not tell us how this induced magnetic field will be oriented. Indeed, there is an ambiguity about this in that the field could either be "up" or "down".

Lenz's law is the addendum to Faraday's law that resolves this ambiguity. During the workshop we concluded that Lenz's law can be stated as:

"The magnetic field that is induced, or created, by a magnet moving through a closed coil will always act in opposition to the original magnetic field of the magnet"

Upon closer examination one can see that this is simply just a **restatement of the law of conservation of energy**. For example, if the induced magnetic field was oriented such that it did not oppose the original magnetic field it would be quite easy to build a device which would produce perpetual motion given a small initial impulse.

Lenz's Law (continued)

Engineering Applications

The following applications are essential applications of Faraday's law, but they rely on the specific results of Lenz's law:

1) *Electromagnetic Brakes*

The braking effect which results from Faraday's and Lenz's law has been put to great use to slow down different types of vehicles. Streetcars, roller coasters, and trains have all made use of these types of brakes, as have certain types of stationary bicycles.

In these brakes, a magnetic field is applied to a spinning metal disk which is attached to the axle of the vehicle. As this metal disk spins, it "sees" a changing magnetic field which causes an opposing induced magnetic field to be created. This is the source of the braking result without any physical contact. The kinetic energy is converted into heat as the induced current flows through the resistive conducting material.

See http://en.wikipedia.org/wiki/Eddy_current_brake for more details.

2) *Magnetically Levitated Trains (MagLev Trains)*

The opposing nature of the induced magnetic field can be used to levitate objects (see the Jumping Ring demonstration below). This has been used in a dramatic way in magnetically levitated (MagLev) trains.

In one type of MagLev train design, a magnetic field is generated by an electromagnet on the train and this field induces an opposing induced magnetic field in coils placed in the track below the train. This opposition between the induced and original fields is what lifts this multi-tonne vehicle off the tracks. Since there is no friction between the train and the rails, these trains can travel extremely fast, with a current speed record of 581 km/h. The main limitation on the speed of the train comes from air resistance.

An interesting video of a MagLev model train can be seen at: http://www.youtube.com/watch?v=TeS_U9qFg7Y. In this video the levitation is due to the properties of superconducting materials, rather than induced magnetic fields. However, it is interesting because it demonstrates the possibilities of this mode of transport.

Lenz's Law (continued)

Possible Classroom Demonstration

Falling Magnets

Below are two variants of the same type of demonstration. In both cases, the braking effect of the induced magnetic field can be observed. In these demonstrations:

- The falling magnet produces the changing magnetic field that is required to create an induced current.
- The induced current will only exist in conducting materials such as copper or aluminum.
- Therefore, the induced magnetic field which opposed the original field of the magnet will only exist for the cases in which the magnet falls near a conducting material. This means that the plastic rod or tube has no effect on the falling magnet.
- Since copper is a better conductor than aluminum, the current induced in the copper rod or tube is stronger. This means that the braking effect on the magnet will also be stronger for the copper than it will be for the aluminum.

<http://www.mip.berkeley.edu/physics/physics.html>, and

U.C. Irvine Physics and Astronomy Lecture Demonstrations, available at
<http://www.physics.uci.edu/~demos/el-mag.html>

Additional Resources

MIT Demonstration of Falling Magnets:

<http://www.youtube.com/watch?v=sPLawCXvKmg>

MIT Demonstration of a Jumping Ring:

<http://www.youtube.com/watch?v=PI7KyVIJ1iE&>

This is a classic demonstration which illustrates the opposing nature of the induced magnetic field through the levitation of a metal ring above a solenoid. A key observation is that it takes a time-varying, or AC current in the solenoid to levitate the ring. This is because a steady, or DC current does not result in the changing magnetic field that is required for electromagnetic induction.

Faraday's Law and Lenz's Law Demonstrations and Explanations:

<http://www.youtube.com/watch?v=kU6NSH7hr7Q&NR=1>

Teach Engineering K-12 Teacher Resources:

<http://www.teachengineering.org/index.php> (main site)

http://www.teachengineering.org/view_lesson.php?url=http://www.teachengineering.org/collection/van/lessons/van_mri_lesson_8/van_mri_lesson_8.xml (lesson plans for Faraday's and Lenz's laws)

Electrical Energy Storage - Capacitors

Summary

The fundamental engineering problem in this workshop was that without a method to store the electrical energy that was generated, the flashlight would just flash, not light. It is essential to store this generated electricity so that it can be gradually used in the flashlight over time, and thus provide a steady light. Capacitors are one way to store electrical energy. The larger the capacitor the more energy it can store.

Engineering Applications

Alongside resistors and inductors, capacitors are one of the fundamental components that electrical engineers work with to design and build electronic circuits. They have many useful properties, and one of these is that they can store energy in an electric form. This property has been exploited by electrical and computer engineers in many applications which involve the storage of both small and large amounts of energy:

1) Computer Random Access Memories (RAM)

The 1's and 0's that are stored in a computer's temporary memory (RAM), are essentially stored in tiny capacitors. These capacitors can be written to ("charged" up with energy) and read (sensing the stored energy), which allows the quick read/write cycle which is so critical for today's high-speed computing platforms. These capacitors can be thought of as buckets. If they are filled with water this represents a 1, and if they are empty this represents a 0.

However, capacitors cannot hold on to this energy indefinitely. Over time this energy is lost since the capacitor is not made from "ideal" materials. It is like a leaky-bucket, which loses its water over time. This means that it must be periodically refilled with water if it is meant to represent a 1. Due to this limitation, a computer must "refresh", or recharge, its RAM every so often. More information, including an animation of the "leaky-bucket" analogy of a capacitor is found at:

<http://www.howstuffworks.com/ram.htm>.

2) Supercapacitors for Electric Vehicles

If computer RAM is one end of the extreme where very small energies are stored, supercapacitors are at the other extreme where massive amounts of energy are stored. This type of capacitor has begun to be used as replacements for rechargeable batteries in buses due to its "green" advantages. One of the main advantages of using capacitors instead of batteries is that capacitors can be charged and discharged over their usable lifetime millions of times as opposed to a few thousand times for batteries. However, batteries are still able to store more energy per kilogram than the largest capacitor presently available. This means that these capacitors must be recharged quite often. In Shanghai, this type of bus, called a Capabus, has been experimented with since 2005 and currently two public transportation routes use this type of bus. Due to the limited range, there are a number of recharging stations along these routes.